Physics of the Cosmos

FIG SAG

Future Innovations in Gamma rays Science Analysis Group

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and YOU!

https://pcos.gsfc.nasa.gov/sags/figsag.php

Status

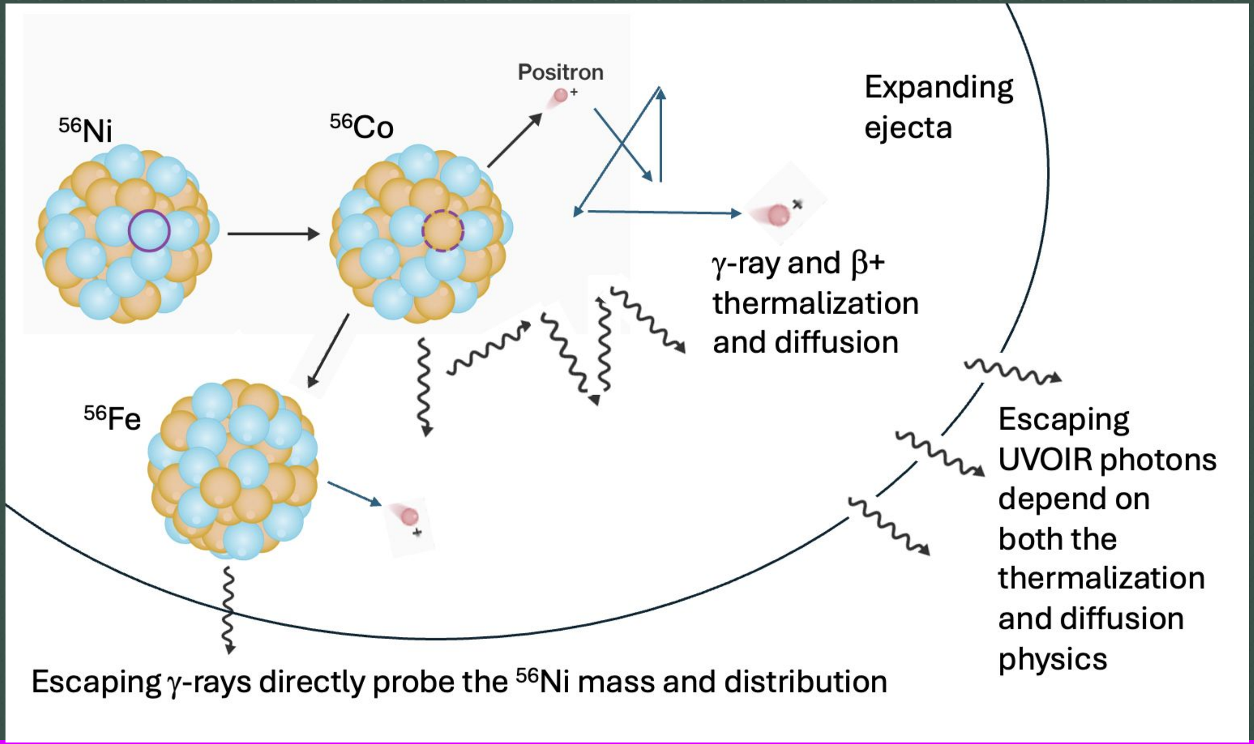
Thank you all for your inputs and discussion at AAS.

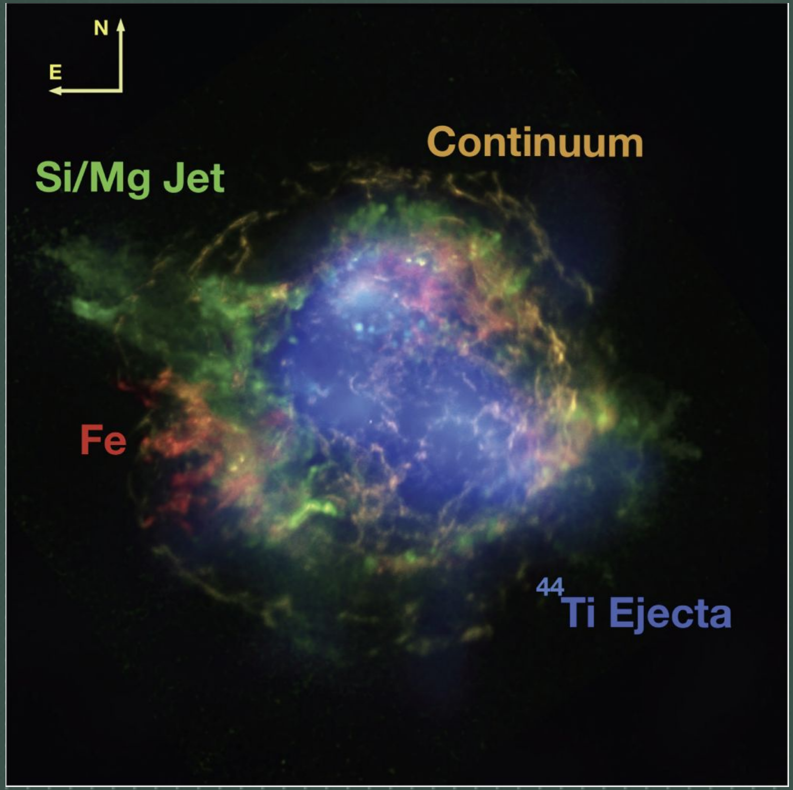
- Overleaf draft is still in active work. Aim to wrap up by end of this year.
- Upcoming in-person meeting at the HEAD meeting in St. Louis
  - Special session on Wed Oct 15 4:15pm
    "Gamma-ray Astrophysics in the 2030's and Beyond: Opportunities, Theory, Technology, and Strategy"
- Special Issue "Future Innovation for Gamma-ray Science" with the Journal of High Energy Astrophysics
  - research note and/or not-yet-published work supporting the FIGSAG report
  - contributions target submission date mid-Nov

Gamma-Rays from Radioactive Decay - Chris

The decay of radioactive isotopes in astrophysical transients provide one of the most direct probes of the engines behind these transients:

- Shock heating/NLTE effects are unimportant for emission model
- e.g. γ-rays from ^{56}Ni SN 1987A drove the development of the now-standard research in the convective paradigm for core-collapse SNe and ^{44}Ti observations cemented this paradigm.





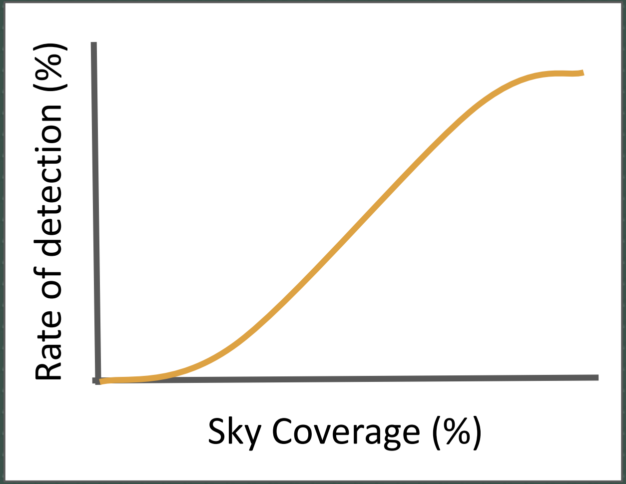
γ-rays provide provide nearly-direct probes of both the nature of the explosion and the underlying physics of wide range of transients including thermonuclear and core-collapse supernovae, gamma-ray bursts (including a range of compact object mergers), novae, and magnetars.

Gamma-Ray Bursts - Chris, Zorawar, Michelle

- GRB engines, emission and particle acceleration
  - Engine power – e.g. by magnetar, accretion disk, black hole spin
  - Jet structure
- Progenitors and classifications – increasingly diverse: short, long, ultra-long, low-luminosity, magnetar giant flare, long-duration merger…
- Cosmology – multi-messenger observations out to high redshifts

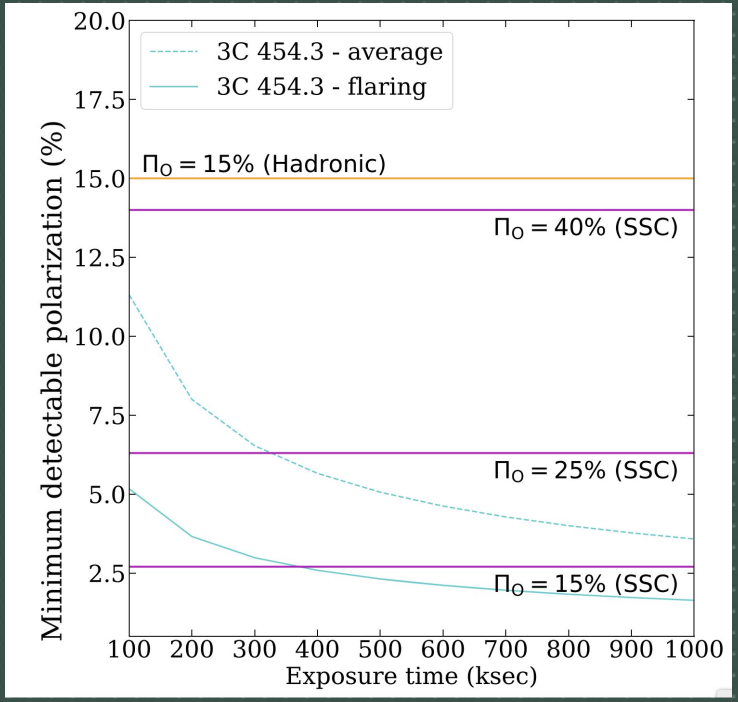
Illustration needed:

- sky coverage vs. detection probability
- sensitivity / energy range vs. distance probed



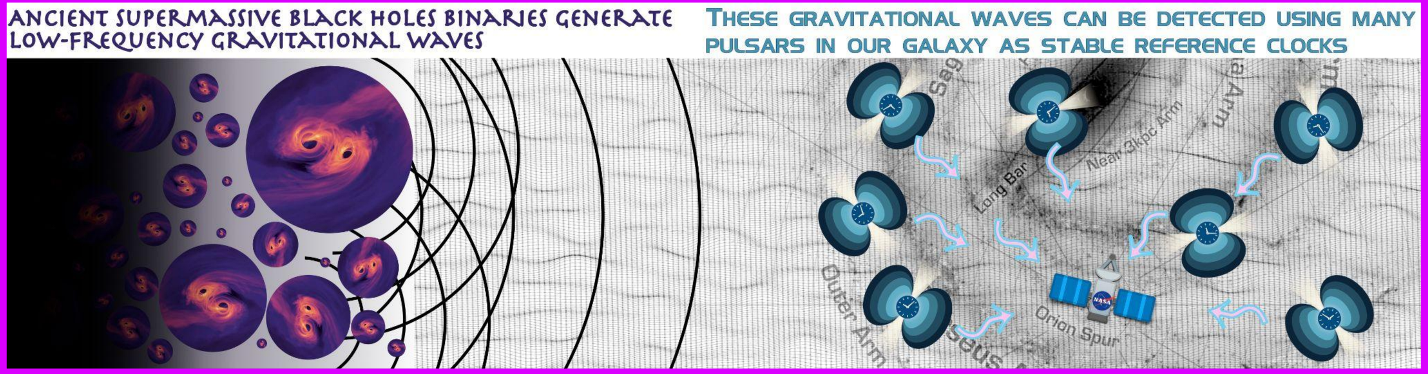
Blazars - Tiffany

- Blazars represent a unique view of the largest astrophysical jets and they are sufficiently long lived to study over time.
- Common questions in blazar physics relate to jet composition, which is fundamentally a question about how jets form, how they interact with the central engine (spin or accretion driven?), which are further related to galaxy and black hole evolution.
    - Spectropolarimetry is most promising and need high effective area, although direct co-detection with neutrinos is also great.
- Jetted active galaxies are also a prime location for cosmic ray acceleration, so understanding particle acceleration processes in blazars is an important piece of the cosmic ray spectrum, which still represents an animated debate.



Polarization vs time (Zhang et al. 2024)

Next Gen Gamma-ray Pulsar Timing Array (PTA) - Zorawar

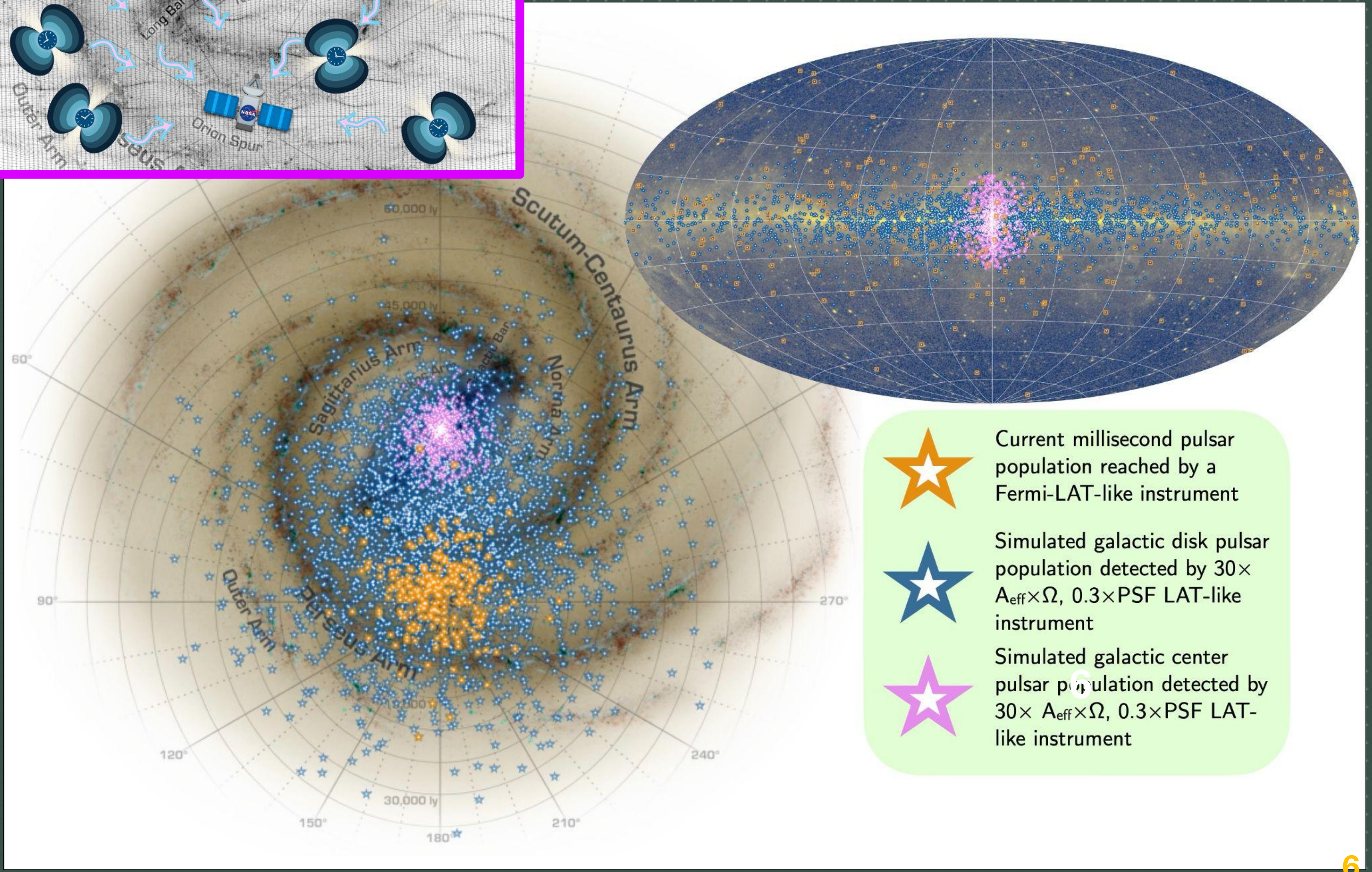


A γ-ray PTA would be totally free of all propagation and multi-instrument systematics complicating radio PTAs;

A 30X FoV*Aeff Fermi-LAT-like instrument with 0.3X the PSF would detect and time ~4000 millisecond pulsars, including those in the galactic center – see right

GW sensitivity: 10^-15 strain amplitude at frequency of yr^-1 in a decade, 2-3x better than radio PTAs, and much better at lower frequencies

ALSO COMPLEMENTARY TO RADIO PTAs!



Next Gen Gamma-ray Pulsar Timing Array (PTA) - Zorawar

ANCIENT SUPERMASSIVE BLACK HOLES BINARIES GENERATE LOW-FREQUENCY GRAVITATIONAL WAVES

THESE GRAVITATIONAL WAVES CAN BE DETECTED USING MANY PULSARS IN OUR GALAXY AS STABLE REFERENCE CLOCKS

Property	Space Gamma-ray PTA	Ground Radio PTA
Uniform and unbiased all-sky coverage of pulsars	👍	
Homogeneous single-instrument dataset	👍	
Retroactive additions of pulsars to array	👍	
Contiguous gap-free and long time span datasets	👍	
Systematics: Free of ionized interstellar medium effects	👍	
Systematics: Free of solar wind/ionospheric effects	👍	
Long-term stability of pulsar pulse profiles	👍	
High precision pulsar single TOA measurements		👍
High signal-to-noise pulsar single TOA measurements		👍
Dynamic allocation of telescope time/resources		👍
Thousands of pulsars simultaneously timed	👍	

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ALSO COMPLEMENTARY TO RADIO PTAs!

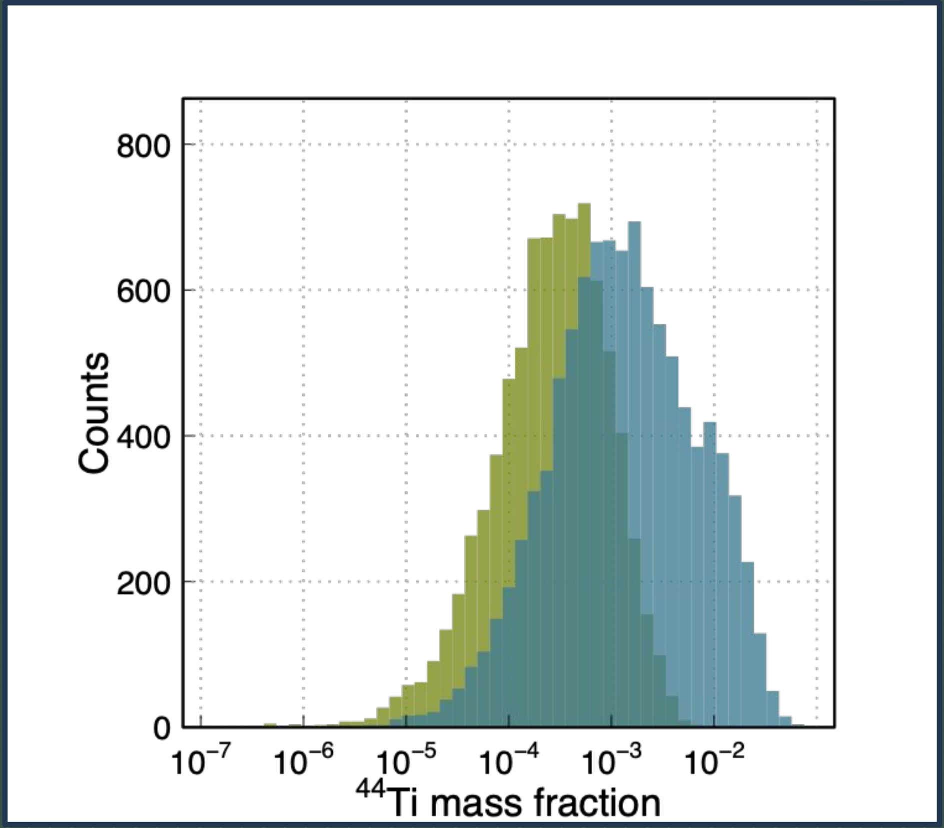
Theory Needs for Gamma-Ray Science - Chris, Tiffany

Many of the theoretical models used to analyze γ-ray data are approximations. As we advance our observations, we will also need to advance the theory. This includes improved models for γ-ray sources:

- Particle acceleration in shocks (e.g. jets, explosions, disks winds):
- Particle acceleration in magnetic fields (e.g. pulsars/magnetars, …)
- Dark matter interactions
- ν interactions
- Radioactive decay

Plus physics modeling hydrodynamics, γ-ray and particle transport, …

These models will require microscopic calculations validated by experiment (e.g. kinetic, particle-in-cell, Nuclear physics, ...) as methods to bridge scales (nuclear networks, diffusive shock acceleration, …)



Uncertainties from the fundamental nuclear cross sections and trajectory assumptions

Capabilities - Michelle

Performance Needs	Nuclear Decay			GRBs	Blazars	PTA	Dark Matter
	Transient	Remnants	Milky Way				
Angular Resolution		10 arcsec - 1 arcmin	<1deg	sub-arcmin for follow-up	sub-degree	0.3 x LAT PSF at 1 GeV	<0.1deg at 1GeV
Field of View		<1deg	Wide field	wide-field		30X LAT FoV*Aeff	>2 sr for transient signatures
Energy Resolution	<1%	<1%	<1%	1% [3%]		Similar to LAT	<1% for lines
Temporal Resolution	~10 days	N/A	N/A	<10μs for GRB QPOs		<30 microsec	
Timing Precision				<10μs for GRB QPOs		<30 mircosec	
Energy Range				keV for prompt, MeV for MGFs, Mev to >GeV	MeV	0.1 to 10 GeV	MeV to TeV
Effective Area				10^-8 erg cm^2 fluence limit for MGFs rate to approach sGRB rate		30X Aeff*FoV LAT	>30x LAT
Polarization				<10% MDP at 0.1-10 MeV	10% in a week [20% in 2 years]	not needed but possibly beneficial	potential unique signatures

Driving Science Cases

- Nuclear Lines - requires high angular resolution and high spectral resolution together
- GRBs - requires high sky-coverage, precision timing, fast alerts (spectropolarimetry would also be useful)
- Blazars - requires high effective area for short timescale spectropolarimetry
- PTAs - requires consistent monitoring over long timescales; fundamentally multimessenger; far more scalable than radio PTAs
- Dark Matter - long timescale problem that unites elements of a lot of other objects under one purpose.

Capabilities - Michelle

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Instrumentation

- Focusing Optics
  - multilayer coatings
  - Laue lens
  - phase Fresnel lens
- Coded Aperture Imaging
- Particle Trackers
  - Compton Telescope
  - Time Projection Chamber
- Detectors
  - Scintillating crystals
  - Transition-Edge Sensors
  - Silicon detectors, CMOS
  - CZT

Capabilities - Michelle

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- Readout Electronics
  - Grid Activated Multi-Scale Pixel readout (GAMPix) for TPCs
  - SiPM readout
  - Fast timing ASIC
- Onboard Processing – enables faster and autonomous decision making.

Mission Architecture and Infrastructure

- Orbits, e.g. cislunar, interplanetary
- Formation Flying
- Fast Comm and High Bandwidth
- Rapid Slewing
- Machine Learning – Event reconstruction, data mining in archives, sky monitoring, extended data fitting in high-level data products.

Summary

- Stay tuned on report draft circulation, goal is to wrap up by end of 2025.
- 🤔 Ideas for next SAG topics for more detailed studies.
- Special Issue “Future Innovation for Gamma-ray Science” with the Journal of High Energy Astrophysics – contribution submission by mid-Nov, please contact us if interested.

Hope to see you at the HEAD meeting in St. Louis!

Special session on Wed Oct 15 4:15pm

"Gamma-ray Astrophysics in the 2030’s and Beyond: Opportunities, Theory, Technology, and Strategy"

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